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PROJECTILE FOUNDATION MOMENT GENERATION PHASE II

Prepared by

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this second phase of the project, an analytical and experimental study was undertaken to determine the restoring or foundation moment of an obturated projectile as it moves down the gun barrel. The first phase of the project showed that for a fixed projectile, this foundation moment was very large, and that for a moving projectile it would be less, but still large. This phase of the project consisted of analysis and test of a

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) projectile which is sliding down the gun barrel. An apparatus was constructed to input a measured angular deflection into the projectile's travel and measure the amount of force which was required to input this measured deflection.

The same conclusions are reached about the foundation moment as were reached in the first phase of this project, namely that it is large. Conclusions are also reached about the efficacy of the finite element method for analysis of this problem and the importance of the properties of the nylon rotating or obturator band.

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I. INTRODUCTION

This study was undertaken as a continuation of a project conducted by Battelle's Pacific Northwest Laboratory under the sponsorship of the U. S. Army's Ballistic Research Laboratory. The purpose of the entire study is to develop methods to measure the magnitude of the restoring or foundation moment generated by the plastic obturator or rotating band when an obturated single bore contact projectile cocks in the bore of a gun during firing. The stability of the projectile is directly affected by the magnitude of this moment. If its magnitude is large, the projectile will potentially be more stable than if it is small. The overall intent of this project, then, is to provide information about single bore contact projectiles which can be used to design a stable, accurate, minimum weight round.

The first year's work showed that in fact this foundation moment is very large. That portion of the study also showed, however, that the magnitude of the moment that can be measured with a suitable test apparatus is strongly dependent upon whether or not the simulated projectile is in fixed or sliding contact with its fixture. A projectile-like device whose plastic obturator band is fixed axially will provide a moment five times larger than a similar device which is allowed free axial movement. The fixture used for all of the testing in the first phase of the project kept the plastic band fixed firmly within a device which was to simulate a short section of the gun barrel. Both the finite element results, and a confirmatory type hand calculation, showed that indeed there is a large difference between a sliding contact and a fixed contact.

In a real gun barrel, the projectile is moving axially at a very high speed. The purpose of this second phase of the project, therefore, was to measure the foundation moment provided by a projectile moving within a simulated gun barrel. This provided several problems which had to be resolved before the actual foundation moment could be measured. The first of these was providing a moving projectile whose motion was similar in nature to a projectile in the bore of an actual gun, but travelling at considerably less speed, and with less acceleration and violence. The second problem was how to input a measurable angular disturbance to a moving projectile, and measure the force or moment required to provide that disturbance. Third, once the data has been taken, how is it to be interpreted in light of the solutions to the first two problems.

This report documents the work done in the past year to provide solutions to the aforementioned problems and provides some conclusions about the action of the obturation bands in service rounds. A geometry was chosen initially for the projectile which was similar to the simplified geometry used in the first year's work. Preliminary finite element analyses were performed to determine the approximate magnitude of the expected moment. Using this information, and a section of gun barrel provided by BRL, a projectile launching and moment measuring system was designed and constructed for the moving projectile tests. Tests were performed using this system, and the data were analyzed to determine the magnitude of the foundation moment. This report, then, documents the analysis, testing, and conclusions reached as a result of this year's work.

II. FINITE ELEMENT ANALYSIS

The finite element analysis performed in this year's work closely parallels the analysis performed during the first phase of the project. Again, the computer code used for all finite element computations was ANSYS(*). Both two and three dimensional analyses were performed using ANSYS, but on significantly different geometries than those used in the first year's work. Figure 1 is a plot of the finite element mesh used for the two dimensional model. ANSYS supports a two dimensional isoparametric axisymmetric element which can be loaded non-axisymmetrically. This element is loaded with a Fourier series loading about the axis of symmetry as was described in last year's report (1). The variation in deflection was again input as the first cosine term of the Fourier series multiplied by the required deflection (i.e. $u = 0.1\cos\theta$). The two dimensional analysis should provide us with accurate results for the cases where the materials remain linear, but the element that we have to use does not support material non-linearity. To model the behavior of material non-linearities, we must go to a three dimensional analysis.

The large central portion of Figure 1 is the simulated bore contact area. The shaded portion of that region is the nylon which is to simulate the obturator or sealing band. The center of the model runs along what is identified as the centerline in the figure. The model was constrained in the radial and tangential directions along the outer edge of the nylon, thereby simulating the gun bore contact. One node at the center of the projectile, centered under the simulated obturator, was also fixed in the axial direction to prevent rigid body motions of the model. The node identified as the displacement input node at the end of the projectile was given a specified displacement in the radial direction. This produced a reaction force at the displaced node which was used to calculate the foundation moment for that value of induced displacement. Reaction forces and overall bulk stresses were also obtained for the plastic obturator. From these values, it was determined that for relatively small displacements, a portion of the nylon obturator material could behave in a non-linear fashion. Also, it was not clear from the two dimensional results how much of the obturator band would be in contact with the gun bore during the angular excursion of the projectile. Three dimensional analyses were performed last year in an attempt to determine the degree of circumferential refinement that was necessary to produce reasonable results for this problem. It was determined that an element size of 15 degrees circumferentially would produce reasonable results, and not be excessively expensive in computer time.

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* ANSYS is a proprietary engineering analysis program owned, marketed, and supported by Swanson Analysis Systems, Inc.

Figure 2, then, is a plot of the finite element mesh used for the three dimensional analysis for this project. This plot has the hidden element boundaries removed for clarity in its presentation. The large shaded section of the mesh is again the nylon simulated obturator band. The flare at the rear of the model is the wobble inducing device, or angular deflection inducing device. Note that the connection between the wobble

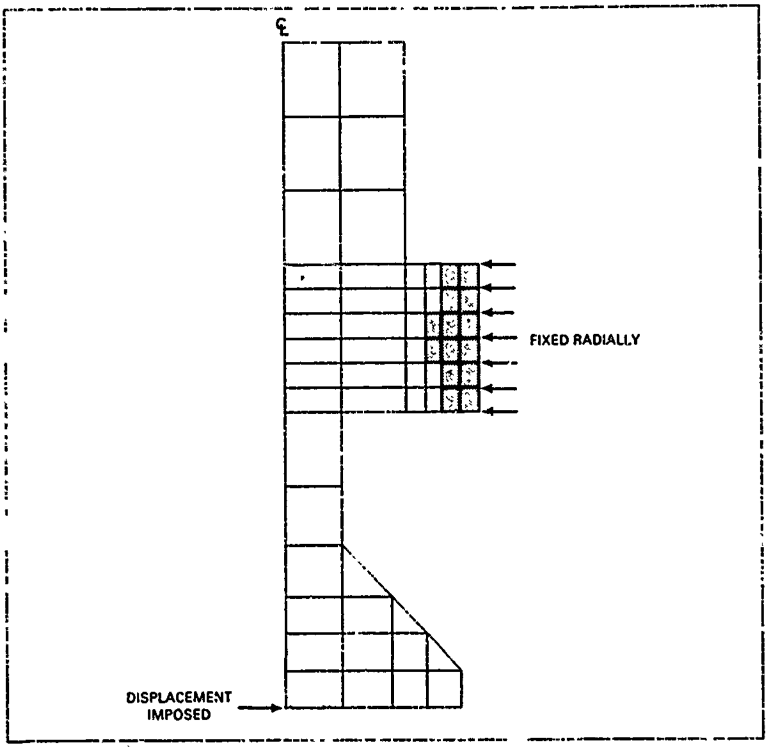

Figure 1. Two Dimensional Finite Element Mesh

inducing portion of this model and the large center section is much fatter than in the previous model. When this project was first begun this year, we were going to use a steel projectile. This is because the test fixture used during the first year's work had to be made out of steel in order to reduce the bending of the moment inducing arm of the fixture. Originally it was not expected that the foundation moment would be as large as it seems to be, and the first fixture was made of aluminum and was designed with a much thinner moment inducing arm. When it was discovered that the foundation moment was indeed large, the fixture was re-designed with a much larger diameter steel moment inducing arm. This year, we expected the same magnitude for the foundation moment and originally designed the projectile out of steel. The original design, however, was much too heavy, and we were forced to re-design with aluminum. This forced us to make the moment inducing arm (the connection between the flare and the large central portion) much thicker.

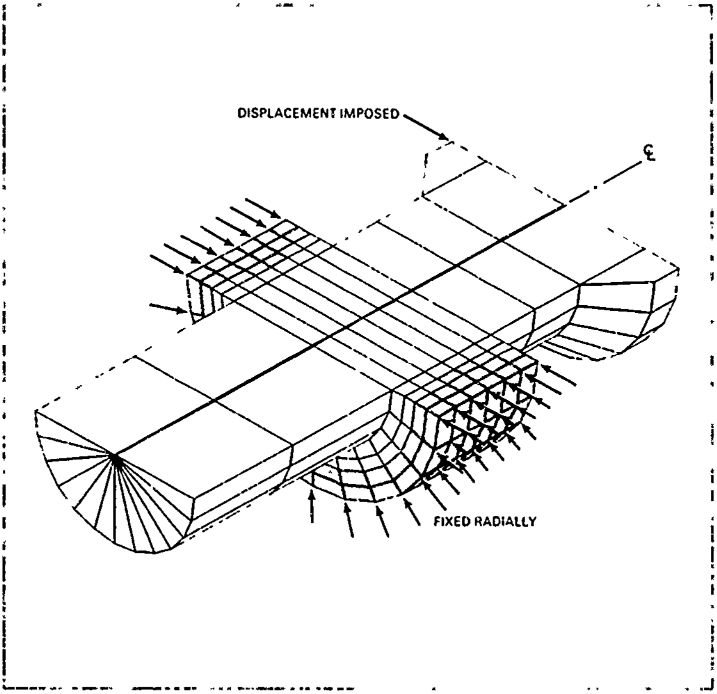

Figure 2. Three Dimensional Finite Element Mesh

At the beginning of the three dimensional analysis, we attempted to use a much more refined mesh than you see in Figure 2. That mesh consisted of 684 elements using a maximum node number of 1279. The solution time estimate for the elastic analysis for this mesh was greater than 6000 seconds on the UNIVAC 1108 computer that was used on this project. This would have cost on the order of $300 per run. Adding inelastic material properties to this analysis would have increased the cost to well over $1000 per run. This was just too expensive for the scope of the project. The mesh that is portrayed in Figure 2, then, consists of 432 elements with a maximum node number of 774. The elastic analysis for this mesh cost approximately $50 per run, or one sixth of the cost of the original mesh. This provided an analysis at a reasonable cost, but it sacrificed accuracy somewhat. This inaccuracy in the analysis will be described later in this report, along with some conclusions about the efficacy of using the finite element method for the solution to this problem.

The same nylon properties were used initially for both the two and three dimensional models. The central portion of the two dimensional model, however, as stated above, was steel. The central portion of the three dimensional model was aluminum. The Young's modulus used for the nylon was obtained from material tests performed on the nylon material purchased for the first year's testing. This may or may not have been the actual value that should have been used in the analysis. We were required to purchase a different product form for this year's testing, as the diameter of the nylon band on the projectile had to be significantly greater than last year's band. Last year, we were able to purchase centrifugally cast Zytel 101 in the small diameter that we needed for those tests. The suppliers of Zytel 101 do not make the spin cast nylon in as large as a 5 inch (13 cm) diameter tube. We therefore were forced to buy extruded tube. This product form should not be significantly different than the spin cast nylon, but may in fact be, as will be described later in this report. We did not perform any material characterization tests on this nylon, as we had extensively tested the nylon from last year, and had a good idea of the behavior of that material. For the analysis this year we initially used the material properties from the tests done during the first year of the project. The material properties used initially in the finite element analyses, then, are as follows:

Material	Young's Modulus (psi/mpa)	Poisson's Ratio
2-D Steel	30×10^6 (207,000)	.3
3-D Aluminum	10×10^6 (69,000)	.33
Nylon	520,000 (3,400)	.4

The results of these analyses, some conclusions about the efficacy of the method for this application, and some re-analysis that was performed because of test results are all presented later in this report. The reasons for this will become apparent in the next section of the report which details the majority of the work done during this year's phase of the project, the testing using a moving projectile.

III. TESTING CONCEPTS

This portion of this document will detail the entire test program that was undertaken for this year's phase of the project. This includes the design concepts and designing of the projectile launching mechanism, the construction of that device, the instrumentation of that device, and the testing itself.

A. Test Concept - Sliding Versus Fixed Projectile

As was mentioned in the introduction to this report, it was discovered in the first year of this project that the foundation moment that could be imparted by a moving projectile is significantly less than that which can be imparted by a projectile which is fixed axially. The testing portion of this year's work, then, was intended to measure just that phenomenon. It was also perceived that if a suitable device could be constructed, the motion of a projectile could be measured and compared realistically to the motions expected in an actual round. This device would have to launch a projectile of a similar weight and geometry to an actual round, at a significantly reduced velocity, and violence, and with the capability of retrieving the projectile easily (and hopefully relatively undamaged). For safety and cost considerations, we were not able to use any pyrotechnics at all. The projectile would have to be launched with a compressed gas, preferably air. To mimic the action of the projectile with actual propellant gasses would require some type of a triggering device which would allow the pressure to change rapidly either at the front or the rear of the projectile. In other words, we would either have to pressurize the entire system, and release the pressure forward of the projectile very rapidly, or have some sort of device which would rapidly pressurize the rear of the projectile.

The pressure curve that a projectile sees during an actual firing has a very short rise time to a peak pressure, and then almost a linear decline after the peak to a muzzle exit pressure. Getting the actual pressures that a projectile sees in firing a gun was impractical in terms of the cost restrictions on the project. As stated above, we could not use pyrotechnics, and there is very little else that produces very high pressures very quickly. We therefore were forced from the outset of the project to use a relatively low pressure system. This required that we use a relatively light weight projectile in order to be able to accelerate the projectile with the low pressures that were required. The low pressures also, however, allowed us to perform the tests within the city limits without too much consideration for the noise that they would produce. These pressures also allowed us to catch the projectile easily and within a few feet of its exit from the system.

B. Projectile Launching Concept

There were two basic requirements for the projectile launching system that had to be met before any design could be attempted. First, we needed some sort of a gun barrel-like device which was of sufficient length and interior diameter to accommodate the projectile and some sort of wobble inducing and force measuring mechanism. This gun barrel also had to be very smooth on the interior, and not be overly costly. The second requirement was a laboratory environment with power, compressed air or gas of some sort, and enough room either inside or outside the laboratory to accomodate the mechanism. The problem of the gun barrel was solved by BRL personnel by donating a short section of an actual barrel. The laboratory space was already available in the form of Battelle's Mechanical Development Laboratory. This lab has a compressed air supply, power, and sufficient space both inside and outside to perform the tests. The lab also has bottled nitrogen, a welding apparatus, and sufficient machinery and tools to construct and alter a test apparatus of this type.

Once these requirements were met, the problem of exactly how the pressure was to be applied to the projectile was tackled. As stated above, there are two methods for applying this pressure, either by pressurizing the entire system and rapidly reducing the pressure in front of the projectile, or by rapidly applying a pressure to the rear of the projectile. We opted for pressurizing the entire system, and releasing the pressure rapidly from the front of the projectile. This option was chosen for several reasons. First, it was difficult to design an adequate receiver tank with a mechanism for releasing the pressure that would not interfere with the projectile itself. Essentially we would have had to have used a rupture disk at the mouth of a pressurized tank. When the disk ruptured, the center of the disk would have impacted the rear of the projectile and caused perturbations in the projectile that would have made analyzing the data impossible. With the pressure being released in the front of the projectile, we were able to design a triggered trap door mechanism that could be re-used for each test.

IV. PROJECTILE LAUNCHING SYSTEM

This section of this report describes the entire projectile launching system in detail. The entire system can be broken into into three basic sub-systems; the gun barrel and receiver tank, the triggered trap door, and the foundation moment inducing and measuring device. Figure 3 is a drawing of the entire system on its mounting with a center cutaway showing the projectile and its wobble inducing and moment measuring device.

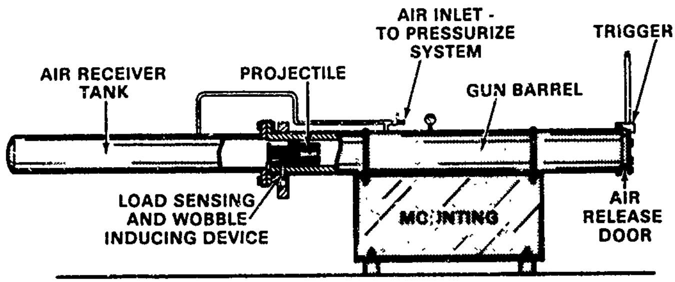

Figure 3. Projectile Launching System

A. Gun Barrel and Receiver Tank Pressure System

The gun barrel and receiver tank pressure system consists of four main components: the gun barrel itself, the receiver tank, the mating flange system between the two above, and the air release mechanism. The last of these has been relegated to its own section of this report. The first three will be described in detail here.

The gun barrel itself is a section of an actual gun barrel which was supplied for this project by BRL. It is approximately six feet in length, with an interior diameter of 5.1 inches. The exterior diameter varies from 6.9 to 7.8 inches, and there is a set of breech threads and a tack welded breech ring at the rear end of the barrel. The barrel looks as if it was originally much longer and has been cut off at what is now the muzzle end. The material of the barrel is reported to be 4340 steel (it was shipped to us as a section of 4340 steel tubing). This steel is fairly commonly used in gun barrels because of its strength, hardness, and resistance to plastic deformation. This also, however, makes the steel somewhat difficult to weld. Its hardness also makes it difficult to cut and drill. Nevertheless, we managed to design a flange for the end of the gun barrel which mates to a similar flange on the receiver tank and to get the flange welded to the gun barrel. A detailed drawing of this flange is shown in Figure 4. The flange is a standard 6 inch pipe flange used in low pressure fluid applications. The gun barrel side of the flange has been machined to provide a mating surface for the breech end of the gun barrel. The inside diameter of the flange has been machined with a ramp which mates on the gun barrel side to the exact inside diameter of the gun barrel and provides a larger diameter on the other side for loading of the projectile within the gun, in much the same manner as the ramp at the end of the chamber in a real gun.

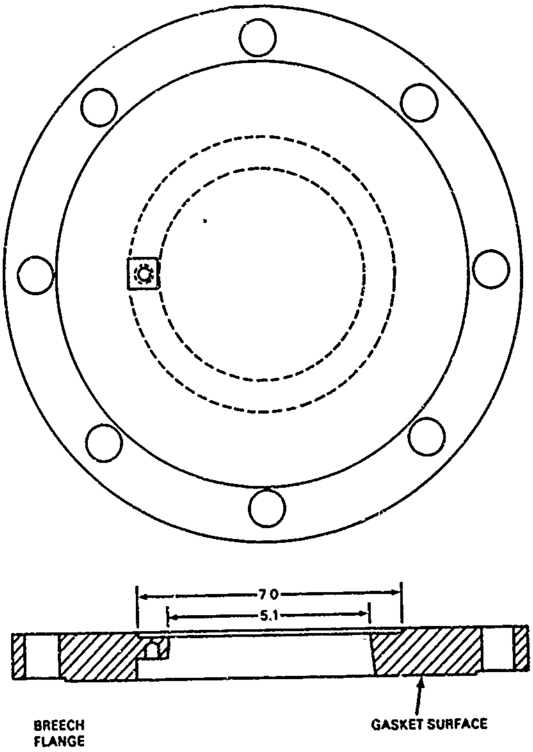

Figure 4. Gun Barrel Mating Flange

The receiver tank which mates with this flange is a 6 foot section of six inch schedule 40 steel pipe with a hemispherical pressure cap welded on one end and a standard flange on the other end which mates with the flange welded onto the gun barrel. The two halves of the flange can be bolted together and unbolted easily, to facilitate loading of the projectile prior to a test. This receiver tank which is behind the projectile provides the impetus when pressurized to accelerate the projectile across the moment inducing and measuring device, and thus, down the barrel to the muzzle. With the triggered trap door mechanism in place, the gun barrel and receiver tank can be pressurized. This provides an equal pressure on both sides of the projectile. When the air release door is released, the air pressure in the gun barrel drops rapidly to atmospheric. The pressure on the front of the projectile then is much lower than that at the rear of the projectile, and the projectile accelerates down the gun bore. The pressure drop in the front of the projectile mimmicks fairly well the pressure rise that occurs in an actual round when the propellant is ignited. In this manner, we can simulate the actual firing conditions that a real projectile will see, without the high pressures, accelerations, and violence of an actual test firing.

As is shown in Figure 3, there is an air inlet system that is used to pressurize the entire apparatus. This system consists of quarter inch copper tubing which is bolted to both the gun barrel ahead of the projectile and the receiver tank behind the projectile with high pressure fittings designed for that purpose. There is a valve which allows air into the system from the laboratory air supply. From there, the air is free to pressurize both chambers at an equal rate and to equalize the pressure both ahead and behind the projectile. The tubing is not large enough, however, to allow the rear receiver tank to de-pressurize rapidly. This allows the device to apply pressure to the projectile as stated above. It also allows the personnel operating the device to stand clear of the entire system when the trigger is pulled.

B. <u>Triggered Trap Door Mechanism</u>

Figure 5 is a schematic of the air release door or triggered trap door mechanism that is used to rapidly de-pressurize the portion of the gun barrel which is ahead of the projectile. A mating flange is welded onto the end of the gun barrel. This flange contains a machined surface on one side to mate to the barrel and a machined surface on the other side used as a sealing surface for an o-ring gasket. The flange is made of 3/4 inch mild steel, and it contains a mounting for the trigger mechanism and the bolts which hold the outer clamping plate. A mating plate with a machined slot for the o-ring gasket is placed against this flange. This plate is the actual gas seal for the end of the barrel and is fitted with the o-ring used to seal against the flange welded onto the barrel. It is also made of

3/4 inch mild steel and is tapped in the center of the side away from the muzzle for a centering bolt which is attached to the outer clamping plate. Another clamping plate (the outer clamping plate) is attached to the sealing plate and is used to tighten the o-ring seal and provide a completely sealed system. The lower end of this clamping plate is placed under two bolts which are bedded into the muzzle flange and act as the lower hinge for the trap door mechanism. The upper end of the clamping plate is placed under the trigger mechanism before being tightened. The triggering mechanism for the trap door is merely an L-shaped steel bar which hooks over the top of the outer clamping plate. This steel bar is through bolted (and thus hinged) to the muzzle flange and has a long steel bar welded to the top for an actuator. As a safety precaution, and so as not to lose the trap door mechanism, a large chain is attached to the door which causes it to be deflected toward the ground, out of the way of the moving projectile. Once all bolts are tightened and the system is pressurized, the trigger mechanism can be pulled, the air release door opens, and the gun barrel ahead of the projectile de-pressurizes very rapidly. The projectile is thus provided with the impetus to accelerate down the gun barrel, past the moment inducing and measuring device.

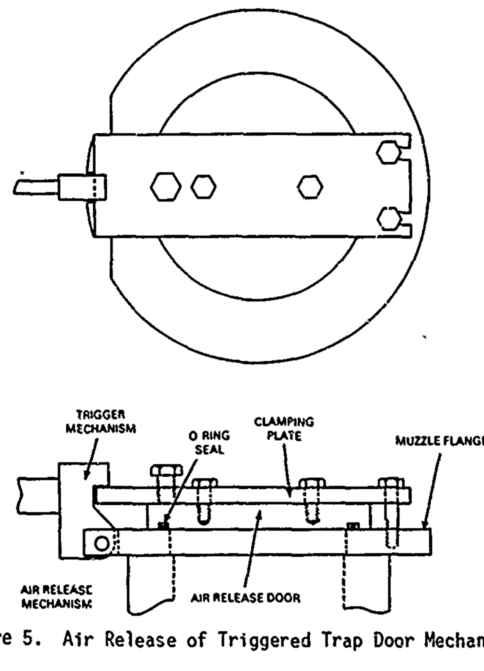

Figure 5. Air Release of Triggered Trap Door Mechanism

C. Moment Inducing and Measurement Device

Figure 6 shows a schematic of the moment inducing and measurement device. There are several components to this system, attached both to the projectile and to the gun barrel itself. The main idea behind the device, however, is that the rear of the projectile is required to climb over a ramp-like device placed on the bottom side of the gun barrel, thus inducing an angular disturbance in its travel down the gun barrel. Beneath this ramp-like device is a load cell which measures the force that the projectile exerts upon the ramp as it climbs over it. The magnitude of the angular disturbance is measured carefully, as is the force on the ramp which causes this disturbance. From these two known quantities, we can measure the foundation moment.

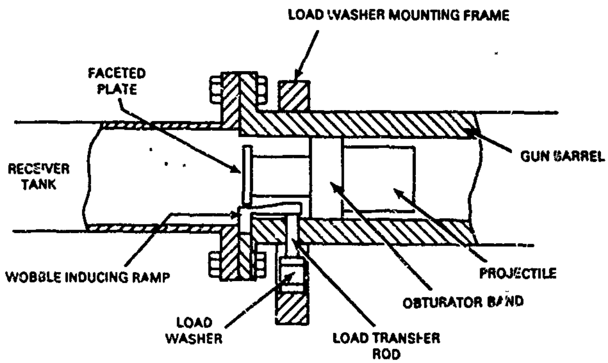

Figure 6. Schematic of Moment Inducing and Measurement Device

The projectile used in the system is shown in Figure 7. Note that the rear of the projectile is slightly different even than the three dimensional finite element model. From early results in the finite element analysis portion of this project, we found that the foundation moment that we would be measuring would probably be very large. A concern was raised at that time about the ability of aluminum to withstand the contact stresses that would be imposed upon the rear of the projectile during the testing. We also wanted to be able to impart different magnitudes of angular disturbance into the projectile, to get an idea of how the foundation moment changes with amount of angular disturbance. Also, it was easier to change the rear of the projectile with each firing than to alter the height of the ramp.

We therefore came up with a faceted steel plate which is placed over the end of the projectile before it is launched. The plate has eight different height facets, each mirrored on either side of the plate. These pairs of facets on the plate are machined to allow a range of displacement of the rear of the projectile from 0.066 inches (0.168 cm) to 0.243 inches (0.617 cm). The rear of the projectile with its faceted plate is required to go over an L-shaped ramp which is hooked over the end of the gun barrel and rests upon the force measurement actuator rod. Photographs of the faceted plate and ramp are shown on the following page as Figures 8 and 9. The faceted plate is made of high carbon steel, as is the ramp. The ramp is further hardened to Rockwell C 55 in order to provide a very hard sliding surface for the faceted plate.

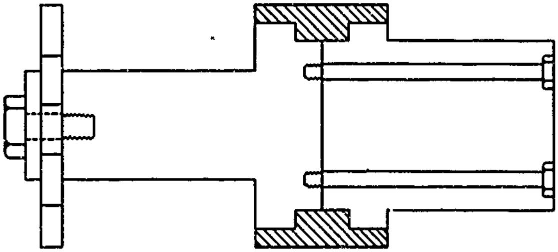

Figure 7. Projectile as Used in Tests

Below the thickest portion of the ramp, going through the gun barrel, is a 1/2 inch steel rod. This is the force measurement rod, and it goes out of the bottom of the gun barrel, through a gas seal, and against the top of a load washer. This load washer is placed within a very large and stiff frame which is bolted around the outside of the gun barrel. The frame was designed to have a deflection that was at least two orders of magnitude less than that which is imparted into the projectile. In this way, the deflection of the measurement device itself could be discounted in our measurements. The thinnest portion of this frame is at the lateral midline of the gun barrel. At this location, the frame is 1.5 inches by 2.0 inches. There are two sides to the frame, and thus, the stress area is 6 square inches. At a load of 10,000 pounds, the maximum deflection that we could expect conservatively would be 0.0004 inches. This is the magnitude of the load that was initially expected for a 0.1 inch deflection of the rear of the projectile. The frame deflection, then, is nearly three orders of magnitude less than the measured deflection and is not accounted for in the analysis of the data.

Figure 8. Photograph of Faceted Projectile End Plate

Figure 9. Photograph of Moment Inducing Ramp

Figure 10 is a detail of this frame. Note that the bottom of the frame has a large open section at its center. The load washer assembly is mounted into this open section and is held in place by the force measurement actuator rod which protrudes from the gun barrel. The load washer is a Kristal Model 9061 Force Transducer which is a piezoelectric device used for measuring very large loads. It has a maximum force measurable in the range of 50,000 pounds force (22,700 kg). The signal from the load cell is conditioned through a Kristal Model 5001 Charge Amplifier and displayed on a Nicolet 2090 Digital Oscilliscope. There is also a laser velocity measurement system which is placed across the path of the projectile to measure the speed of the projectile as it exits the muzzle. Originally the signal output from the charge amplifier was routed to a Teac Model SR-50 14 channel FM data recorder. The signal from the tape recorder was analyzed initially, and it was found that the rise time on the signal exceeded the frequency response of the tape recorder. The only device available to us at the time to record the event was the Nicolet digital oscilloscope. After the first two tests, the Nicolet was used exclusively to record the response of the Kristal load washer.

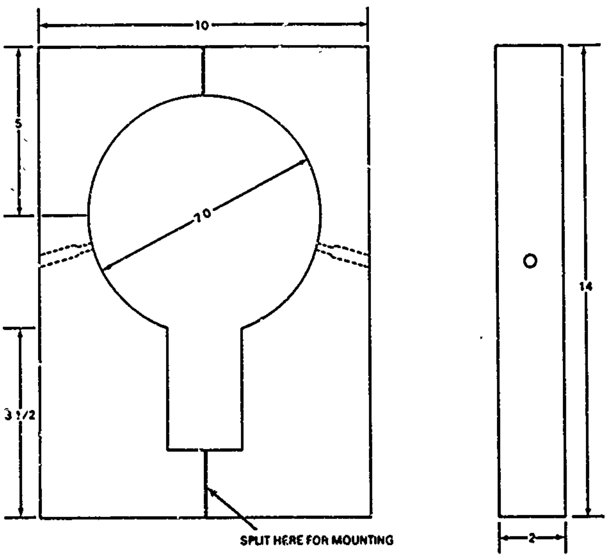

Figure 10. Load Washer Support Frame

V. TEST RESULTS AND BAND DESIGN CHANGES

The testing phase of this project was started in April of 1983. Initially, we tested the air pressure system and the trap door mechanism. These tests also gave us confidence that the pressure system was going to function as designed. In these tests, the system was dry fired, without the projectile. We mounted the receiver tank to the gun barrel, closed and sealed the trap door, and applied air pressure slowly to the system. The maximum air pressure available in the building was 120 psi (830 kpa), and we pressurized the system to that level. Once that pressure had been obtained and maintained for a sufficient length of time, we actuated the trigger mechanism to release the air pressure. This gave us some idea of the recoil that we would expect from the device and a conservative estimate of the noise level that the gun would produce. With no projectile in the barrel, the entire system de-pressurized in these tests rather than just the gun barrel in front of the projectile. This produced the loudest report that the system could produce at that pressure. The noise from the device attenuated rapidly as it travelled away from the MDL building, and did not cause a noise problem. Also, the mounting held the assembly fixed well enough that we could not see any appreciative recoil from the mechanism. The mounting was bolted to the concrete prior to the tests to alleviate any potential recoil problems.

The next tests that were performed included the projectile, but not the moment inducing ramp mechanism. The projectile was loaded into the system, the system was again bolted together, and the air release trap door was mounted and sealed. Again the maximum building air pressure was applied to the system (120 psi or 830 kpa), and the triggering mechanism was actuated. The projectile shot out of the gun tube at what appeared to be 338 feet per second (111 meters per second). Subsequent shots with the projectile showed us that our laser velocity measurement device was being affected by the moisture in the air which preceeded the projectile. Essentially, the cloud of gas that came out of the gun ahead of the projectile was cutting the path of the laser enough to trip the device. We moved the sand box which catches the projectile farther from the muzzle and moved the laser device farther from the muzzle. This corrected the laser tripping problem. The projectile speeds that we measured after this problem was corrected were more in the range of 160 feet per second (52 mps) which is very close to the velocity that we originally expected the projectile to attain.

After the preliminary work of pressure testing the assembly, and firing the projectile without inducing a wobble, we were ready to fire the projectile with the wobble inducing device placed in the gun barrel. These tests were first performed with the air intake to the system mounted on the gun barrel. This configuration caused the pressure to be slightly higher in the front of the projectile during pressurization of the system than it was at the rear of the projectile. The projectile slid backwards slightly during this pressurization. This forced the ramp to move away from the end of the gun barrel slightly. On the third test, the long portion of the ramp broke off at the position shown in Figure 11. To cure this problem, we re-mounted the air supply line onto the receiver tank so that it would always be at a higher pressure than the gun barrel, forcing the projectile forward onto the ramp, and not allowing the ramp to move axially when the gun was fired. The second ramp that was made to replace the broken one has been in service since that time.

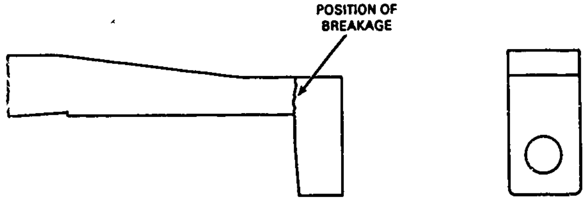

Figure 11. Moment Inducing Ramp Showing Position of Breakage

The plate which rides up over the ramp and induces the wobble into the projectile has eight facets, as stated before. Those facets allowed us to input differing magnitudes of angular disturbance into the projectile during its motion down the gun barrel. The magnitudes of those eight steps are shown in Table 1 below. The values in the table are given both for the angular disturbance at each step (in degrees) and the actual displacement of the rear end of the sabot produced by that facet sliding over the ramp. The displacements range from less than 0.1 inches to nearly 0.25 inches. This gave us a very broad range of disturbance in which we were interested, from a purely elastic nylon behavior to an elastic-plastic behavior of the nylon band material.

Table 1. Magnitudes of Disturbance for Each Facet

Step	Angular Disturbance (deg)	Displacement (in/cm)
1	0.75	0.066/0.17
2	1.1	0.093/0.24
3	1.3	0.11/0.29
4	1.6	0.14/0.36
5	1.9	0.16/0.41
6	2.2	0.19/0.49
7	2.5	0.22/0.55
8	2.8	0.24/0.62

Note that the amount of angular disturbance that we imposed upon the projectile is rather small. The expected foundation moment generated from this angular disturbance, however, is very large. In the case of facet 3, we fully expected a force of nearly 10,000 pounds (4500 kg) to be exerted on the top of the ramp when the projectile passed over it.

The first test results that we obtained are shown below in Figure 12. The forces that we measured initially with the system were much lower than those that the finite element analysis had predicted. The nylon band on the projectile in those early tests was machined to fit snugly into the bore of the gun barrel. We did not initially have any interference between the barrel and the plastic band. When the projectile cocked in the bore, portions of the nylon band lost contact with the barrel and were not providing any moment. In an actual gun firing, the obturator band is forced into the barrel through the forcing cone, and there is a large interference generated. We came to the conclusion that we needed at least some interference between the nylon band and the gun barrel to simulate the actual firing of an obturated round. The reason that we had not provided this interference in the first place was the problem of loading the projectile into the gun barrel. The design of the original obturator band precluded any possibility of expanding the band once the projectile was in the bore. We therefore had to find some method of pushing an oversize projectile into the gun barrel.

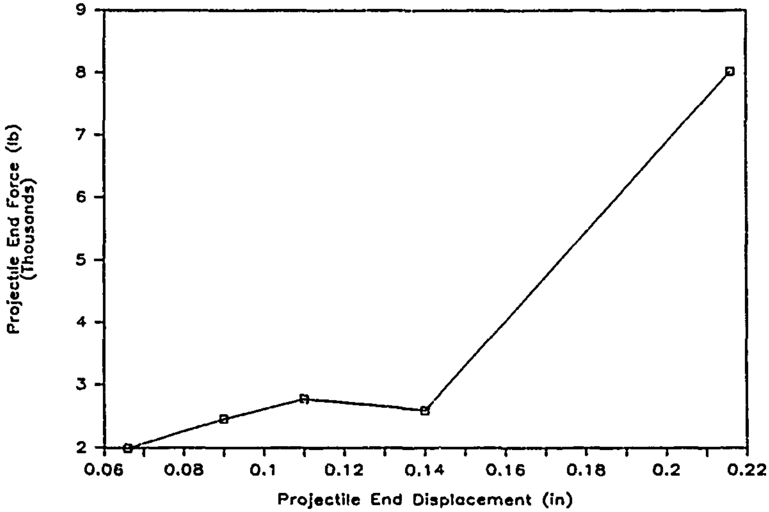

Figure 12. First Test Results

The next series of tests that were run were performed with an obturator band with a fairly large interference. Initially, we tried to get a projectile with an interference of 0.040 inches (0.1cm) into the gun barrel. We devised a hydraulic jacking system which attaches to the flange on the rear of the gun barrel and applies a force to the rear of the projectile to push it into the gun barrel. We could not get the first projectile into the gun barrel with our hydraulic system, and we were forced to machine off some of the outer diameter of the nylon band. The band which we were finally able to load into the launching system had an interference of approximately 0.01 inches (0.025cm). We wanted all parts of the nylon band to remain in contact with the gun barrel during firing so that we could compare the results with the finite element model. This necessitated using only the first facet on the projectile back plate. Any larger disturbance would have caused some portion of the nylon to lose contact with the gun barrel.

It required approximately 16,000 pounds force (7300 kg) to push the projectile into place in the gun barrel. During the loading of the projectile, we noticed that the hydraulic ram seemed to cause the projectile to overcome its static friction and move suddenly. We would then have to apply a load to the rear of the projectile, and it would again pass a static friction threshold and move suddenly. We used this observation to advantage when it came time to fire the projectile. It was obvious that the building air supply would not provide a high enough pressure to overcome the static friction of the projectile in the bore of the gun. It was also obvious that our air release mechanism would probably not remain sealed at the pressure that would be required to fire the projectile. We therefore left the air release door off the muzzle end of the system and merely applied pressure to the rear of the projectile through the receiver tank. This method worked very well. The projectile required 615 psi (4240 kpa) to overcome static friction and begin to move in the gun barrel. Once this pressure level was reached, and the projectile began to move, it accelerated very quickly down the gun barrel, and exited at 273 feet per second (90 meters per second). This made us comfortable that the procedure would work and that the data would not be adversely affected. This method, however, uses up a nylon band on each shot. The nylon begins to be deposited on the inside of the gun barrel about two feet (0.6 meters) from the breech, leaving a very thin film of nylon on the interior surface of the gun barrel. With this erosion of the nylon band, the band diameter at shot exit is only slightly over the diameter of the muzzle. This procedure also does not mimic the action of an actual firing as well as does the system with the trap in place, but was necessary in order to collect meaningful data.

Once we were convinced that the new technique would work, we had three more plastic bands machined and we fired the system three more times. The measurements of those bands and pertinent projectile loading information are presented in Table 2 below. The data from the four firings is presented in Table 3. Note that the second of those bands did not require as much force to seat in the breech, nor as much pressure to fire as the first band. The projectile in this case in fact did not exit the muzzle during its initial travel down the gun barrel. The load data from this projectile is, therefore, suspect. The other three projectiles fired in a consistent manner, however, and the data from those tests is probably useable.

If we make the assumption that the average of the values in Table 3 minus the second entry gives a good indication of the actual foundation moment in an actual round, we can make an estimate as to the importance of this moment as a stabilization mechanism for the round. For instance, let us determine how far back the center of gravity of the round would have to be to equal the foundation moment in an actual case. The maximum acceleration that most tank rounds see in the gun is about 50,000 g's. Let us take for an example the 120mm gun system and a postulated projectile weight of 16 pounds (7.3 kg). The average foundation moment that we measured was 36,700 in-lb (42,300 cm-kg) at a deflection of 0.066 inches (0.168 cm) or 0.76 degrees. This means that the center of gravity of the round would have to be approximately 3.5 inches (8.9cm or 89mm) or roughly two thirds of a caliber behind the center of the obturator band to equal the foundation moment provided by the obturator band. This is also at the maximum acceleration of the round. At any other time, the nylon band would provide the same magnitude of foundation moment, but the lesser acceleration on the round would lessen the action of the center of mass.

Table 2. Band Measurements and Pertinent Firing Data

Band	Diameter (in/cm)	Force to Load (lb/kg)	Pressure to Fire (psi/kpa)
1	5.112/12.98	15,840/7200	615/4240
2	5.112/12.98		355/2450
3	5.112/12.98	16,200/7360	480/3310
4	5.111/12.98	9900/4500	510/3520

Table 3. Test Results With Band Interference

Band	Force on Load Cell (lb/kg)	Foundation Moment (in-lb/cm-kg)
1	9200/4180	46,000/53,100
2	5530/2510	27,650/31,900
3	6660/3030	33,300/38,500
4	6200/2820	31,000/35,800

VI. RESULTS OF FINITE ELEMENT ANALYSIS AND COMPARISON TO TESTS

Initially, the finite element analyses were performed with the assumption that the nylon band material always came into contact with the gun barrel. Both the two and three dimensional analyses were performed in an effort to gage the magnitude of the largest forces that we would be measuring and to gain some confidence that the finite element method might produce accurate enough results for design type calculations. The magnitude of the highest forces that we would be measuring would drive the design of the projectile and load measuring system. More importantly, the suitability of the finite element method for predicting foundation moment is a very important part of the overall aim of the project - namely: to provide BRL with a method with which to design an accurate, minimum weight projectile system with a single gun bore contact.

At the first of this year's work on this project, some time was spent in attempting to write a computer program that would provide this design method. The outline for the program was generated, and some FORTRAN code was written which would eventually have led to a complete system for modelling the motion of a single bore contact projectile in a smooth gun tube. The equations of motion of the system are fairly straighforward, as the motion is basically axial, with perturbations only in two directions. It soon became evident, however, that the one quantity that could not be easily estimated within the structure of this program was the foundation moment itself. That is, once this quantity is known, the rest is very simple. The only likely candidate for a computer generated solution for the foundation moment is the finite element method. This fact provided the impetus for comparing the results of the tests with the finite element results and determining whether or not the method would provide us with good estimates of the foundation moment.

With this in mind, let us look at Figure 13, the results of the linear elastic finite element analyses that were performed using the models previously described in this report. Also presented in this figure are the first test results, the test results with the interference, and the results of an analysis that takes into account the fact that some of the nylon is not in contact with the gun bore. This was done by relaxing the boundary constraints for several nodes on the outside of the nylon where it would otherwise contact the bore of the gun. The nodes whose boundary constraints were relaxed were chosen on the basis of the reaction forces at the nodes for the analysis with all outer nylon nodes fixed. Those nodes that exhibited tensile reaction forces in the first analyses had their radial constraints relaxed in this analysis. Some adjustment was required after the initial relaxation in order to get only those nodes that were in tension relaxed, and no others. These results, then, should match those cases where there is no interference between the nylon band and the gun barrel, as in the first series of tests. You can see in fact that the finite element results and the test results do not match well. The two dimensional results come fairly close to matching the test results, but the three dimensional results are very high.

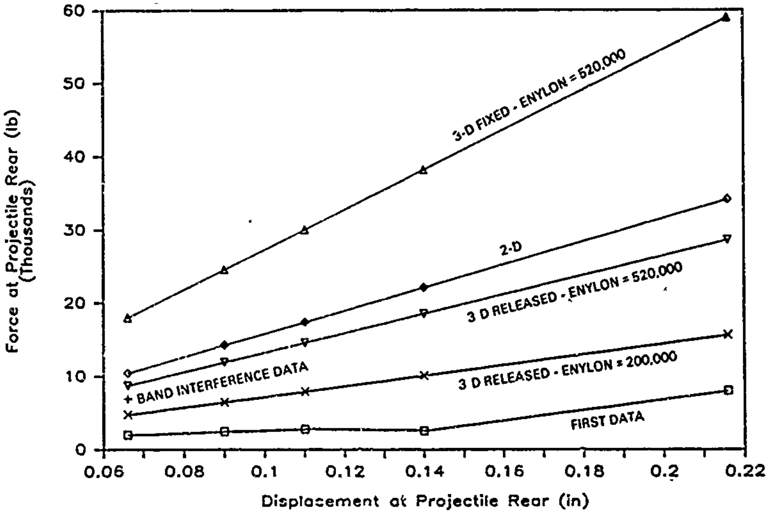

Figure 13. Finite Element Results and Test Results

One of the things that is probably causing the differences between test and analysis is that the finite element results are for a linear elastic nylon material with the dynamic Young's Modulus used rather that the static value. In being linearly elastic, the calculations do not take into account any inelastic deformation. The stresses in the outer elements of the nylon are above the quoted yield strength of the nylon even at the relatively small angular disturbances. Also, the event does not happen quite as fast as the high strain rate tests were performed, and using the dynamic properties for the anlysis may not be entirely correct. There is another factor influencing the real situation that we have not taken into account in these calculations. This is the action of the propellant gasses on the rear of the projectile. The propellant pressure at the rear of the obturator band in most of the high performance KE rounds that have been designed is in the range of 50,000 psi at maximum launch pressure. This puts the band into a state of hydrostatic compression. The behavior of the nylon band under these conditions is not as yet known. There is yet another material property question that has not been answered. The material properties used in the analysis were for material bought for the first year of the project. This material was centrifugally cast, and was purchased from a different supplier than the material for this year's testing. The material used for the testing this year was extruded tube. The centrifugally cast material did not come in large enough diameters or wall thicknesses for the test projectile this year. This material had a different "feel" and look than last year's nylon, but it was assumed that the material would behave in a similar fashion. That may or may not be a good assumption.

There is also another possibility for discrepancy in the results. The original finite element mesh designed for the analysis this year was much finer than what is shown in Figure 3, as was stated earlier in this report. The usual result of a too coarse mesh is that the structure seems to be more stiff than it actually is. This could easily be the case in this analysis. If one looks at the difference between the two and three dimensional results in this light, the mesh refinement difference becomes very apparent. In the two dimensional analysis, the mesh can be thought of as infinitely fine in the circumferential direction. The three dimensional analysis, however, uses a circumferential element size of 15 degrees. This size was adequate for the small diameter test fixture used last year, but probably is not fine enough for the large diameter projectile used in this year's testing. If this is the case, and our mesh was indeed too coarse, the results are then at least trending in the correct direction. That is, the coarser mesh is acting as if it were stiffer than the more refined mesh, and it provides a higher number for the reaction force at the moment inducing end of the projectile.

VII. CONCLUSIONS

There are several conclusions that can be drawn from the results presented in this report. First, the foundation moment for a moving projectile still seems to be very high. The best way to measure the relative importance of this quantity is to relate it to that moment produced by the center of gravity being behind the center of pivot for the round and the round cocking slightly in bore. To equal the righting or straightening moment produced by the nylon band in our experiments, the center of mass would have to be roughly two thirds of a caliber behind the center of pivot at the maximum acceleration that a common KE round sees in bore. This magnitude is very significant in light of the desire on the part of BRL to produce accurate, light weight projectiles whose performance exceeds current design technology. This conclusion supports the work done the first year on this project and the conclusions reached at that time. In any analysis of the motion of a single bore contact projectile during firing the foundation moment should be taken into account, as it is not a small effect. It will, in fact, have a predominant influence on the ability of BRL to design a single bore contact projectile which will provide needed accuracy.

The ability to evaluate the foundation moment for any design is also desirable in light of its importance in the motion of the round in the bore of the gun. This ability is, in fact, manditory for a complete design of a single bore contact projectile. The most promising method of providing this evaluation is the finite element method. We have shown, in this year's analysis and test, that the application of the finite element method to this problem is not a straightforward one. It is, in fact, fraught with all of the difficulties that are inherent in attempting to model a real event with real materials using approximate methods. Sometimes the approximate methods are not adequate to accurately model the physical event, or the approximations that we make upon using those methods are not adequate to simulate a real event. That is the case in the analysis work that has been done this year. Too little was known about the inelastic or non-linear properties of the nylon that was used as obturator material. Too little was also known about the amount of the nylon material that actually comes in contact with the gun bore, and about whether or not the projectile end displacement that we thought we were measuring was in fact how much the projectile was displaced.

There are several things that can be done to alleviate most of the inconsistencies that have been identified in this report. Of primary concern are the inelastic or non-linear nylon properties. Any future finite element analysis will have to take into account those properties. This means that we will be required to perform material characterization tests on the actual band material after we receive it from the supplier and before we attempt to model the projectile. Also of prime importance is to accurately measure the displacement that the projectile is seeing when it climbs over the ramp. Each projectile band was machined down to its final diameter by spinning the projectile with band in a lathe. This should provide an outer band surface which is as parallel to the centerline of the projectile as possible. In any future testing, this will have to be a measured quantity, and will have to be taken into account in the data.

VIII. PLAN FOR FUTURE WORK

There are several questions which remain un-answered at the end of this phase of the project. Three of those questions can be answered within the scope of the third and last phase of the work. First, in what way do the non-linear material properties of the nylon band have an effect upon the foundation moment. Second, and possibly most important, will the finite element method be an effective tool for BRL to evaluate the foundation moment for any particular projectile design. Third, what effect does changing the geometry of the band have on the foundation moment. The first two years of this project have concentrated on basically one band geometry. This geometry is a fairly simple one to analyze, and to construct, and as such has been used extensively. It is not, however, entirely characteristic of the common band designs used on the 120mm KE rounds.

The non-linear or inelastic properties of nylon at the strain rates and loads that exist in a gun bore are not well known, as has been stated previously. One of the tasks in the third phase of the project would be, then, to design and run material characterization tests that will give us the correct properties to use in our finite element analysis. The nylon is essentially under hydrostatic compression in the gun during firing. The cocking of the projectile in bore adds another additional load to the nylon which must be accounted for in our analysis. Thus, we will need properties of the nylon which will describe the response of the material to those loads.

Once material characterization tests have been performed, a finite element model of the projectile being tested would have to be constructed. This model would have to use a mesh which is much finer in element size than the mesh used for this year's work, and would have to take into account the inelastic properties of the nylon band material.

When the finite element results finally match the test results, and we are confident in the method, at least one different band geometry would be tested and analyzed. This band geometry would be more characteristic of the geometry of the current 120mm KE projectile. This would provide evidence of how the foundation moment is affected by band geometry and allow BRL to make rational choices for that geometry in their designs.

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